Life Cycle Assessment of Pellet Burning Technologies

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Foreword and acknowledgement

This thesis addresses a life cycle assessment of the carbon neutrality of wood pellets as a heating fuel. The main researcher on this project is Tom de Haan, a student in the Bachelor of Science program ‘Science, Business and Innovation’ at VU University, Amsterdam.

The life cycle assessment will not only put emphasis on the carbon dioxide balance, but also on government policy around pellet heat. Ultimately, links between policy and carbon emissions will be investigated.

The host-organization of this research is The Alliance for Green Heat, a non-profit organization, educating the public and policymakers about wood as a heating fuel. Hereby, I would like to gratefully thank John Ackerly, President of The Alliance for Green Heat for his guidance and for accommodating this research.

I would like to thank David Ackerly, associate professor at University of California, Berkely and member of the Alliance for Green Heat advisory board, William Strauss, president of Futuremetrics, Jan Dekker, senior lecturer at the Department of Biophysics of the Vrije Universiteit Amsterdam, Bart Bossink, professor in Technology and Innovation at VU Amsterdam and Peter van Hoorn, lecturer at the Department of Spectrometry of the VU Amsterdam, for their feedback and assistance during the research and the writing of this thesis.

Executive summary

In this paper, a Life Cycle Assessment (LCA) of the CO2 balance of pellet heating appliances is executed. Trees take up Carbon Dioxide, the most predominant cause of the Green House Effect, and store this as elemental carbon. Carbon, fit for fueling purposes, is located in the aboveground biomass, root biomass, forest floor litter and in the soils. In the first section of this paper, this uptake is subject of analysis.

Second, an examination of the processing of wood to pellets follows. The wood is harvested, transported, dried, converted into pellets, and transported again for retailing in either the USA or Europe. In both cycles, two different means of drying the wood can be applied, and in order to gain insight in different real life applications of the wood, both are examined.

Emissions of pellet-fueled appliances form the third part of this cycle: The emissions of a pellet boiler of 7 kW and a pellet burner connected to a water reservoir of 20 kW are examined. Besides CO2, these appliances emit small amounts of CO, CH4 and Benzene.

In addition to analyzing the technical and lifecycle aspects of pellet heating, emphasis is put on the policy around pellets as a heating fuel in the US. This paper describes the programs that the US government currently has in force to promote the use of pellets. Consequently, this paper attempts to establish links between the life cycle and policy. As will become clear, however, it is difficult to draw unequivocal conclusions with respect to the impact of these programs is on the production and use and on the CO2 lifecycle as a whole, of wood-pellets in the USA. There seems to be a correlation between the Biomass Crop Assistance Program, that supports the growth, production and storage of bio-based fuels, such as wood pellets, and the actual production of the pellets. It is not clear, however, how strong this correlation is. This outcome provides an opportunity for further research. Also, the role of the government in the System of Innovation of wood pellets is described. The government appears to stimulate both the technology and the consumer-side of the chain. The programs fostering innovation, however, are all intended for renewable energy in general and no programs exist intended purely for wood pellets. It is therefore hard to examine the exact influence of the government in this System of Innovation and this provides an opportunity for further research.

Pellet use leads to emission as low as 6.04 g CO2/MJ, whereas the lowest polluting fossil fuel emits 62.8 g CO2/MJ. The most important conclusions in this report are that the used wood must, ideally, not be shipped from the West Coast of Canada to Europe and the wood used must be harvested sustainably for the carbon neutrality to be maintained. The latter aspects in the LCA and logistics chains are the most important features of the delicate CO2 balance of this source of heat. Debates about this topic are still in progress, both among scientists and legislators, and provides, in itself, a great opportunity for further research.
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1 Introduction

Until the 1940s, over 20% of the American population used wood as its predominant source of domestic heat (US Census data). After a steep decline in use over the last decades, individuals and governments are increasingly acknowledging the potential of wood as a clean, renewable and sustainable form of energy. This acknowledgement finds its rationale in the balance between carbon dioxide absorbed from the atmosphere by trees and the carbon emitted by wood burning appliances.

Since the late 1990s, the usage of wood pellets has increased. These pellets are chunks of condensed sawdust, usually obtained from sawmills. Pellets are used, rather than chips or logs, as they have a homogeneous composition and low moisture content. This results in a continuous combustion and low emissions of byproducts. Pellet-fueled appliances are generally marketed as carbon neutral, so the dynamics of the carbon cycle will be researched in this study.

The technologies highlighted in this study are a modern pellet stove and a modern pellet burner. The pellet stove radiates heat directly from the burning pellets into the room, whereas the pellet burner heats up water that, in turn, will heat a space.

A Life Cycle Assessment (LCA) according to the methodology of Setac (1993), is the used technique to assess the CO2 neutrality. A Life Cycle Assessment is a technique to systematically assess all the inflows and outflows of a product, from cradle to grave. For pellet heating this cradle-to-grave analysis starts with the growth of wood, continues with the processing of this wood into pellets and concludes with the combustion of wood pellets in either of the two appliances.

In this LCA of the carbon cycle of wood as a heating fuel there will be emphasis on (in)efficiencies as well as C capture, waste streams and emissions across the cycle.

As the ultimate purpose of using wood rather than fossil fuels for heating is mitigating climate change, another interesting direction to look at, is policy. Therefore, a policy analysis will be made in which the initiatives regarding pellet heat by the US government will be examined. This policy analysis investigates the role of pellets as a heating fuel as a tool for fighting climate change. Also, this paper describes the role of the government in this System of Innovation.

Finally, links are investigated between (in)efficiencies in the carbon cycle and government policies. Additionally, the role of government policy on innovation is stressed.

The structure of this document is as follows: First, the methodology of the Life Cycle Assessment is described and all the inflows and outflows of the system are listed. An analysis of this listing is made and the carbon balance of pellet burning appliances is calculated. Then, an analysis will is of the different policy initiatives by the US federal government on pellet heat. First, the initiatives will be listed, and later these initiatives will be connected to different parts of the cycle and an attempt will be made to determine to what extent policy influences carbon neutrality and wood pellet usage. This study ultimately addresses the extent to which the technology is carbon neutral and what the role of policy is in this perspective. The cycle as described in this paper has been segmented in order to get insight into where the biggest carbon losses and gains occur.

2 Methodology: Life-Cycle Assessment

Life Cycle Assessment, as described by SETAC (1993), is the method used to assess the efficiency of the carbon cycle of pellet burning appliances. According to SETAC, the following components have to be considered, in order to perform an accurate Life Cycle Assessment: Goal definition and scoping, Inventory analysis, impact assessment and improvement assessment. Duda & Shaw (1997) define these steps as follows: The first stage, goal definition and scoping, sets boundaries for the study. This chapter contains the scope, the functional unit and a strategy for data collection. The idea of a LCA is to survey all energy and material flowing in and out of the final product. In order to do this, one has to establish boundaries between the system and the environment as well as between the studied system and the other product systems. The limitations of the research have to be reported. A significant part of the scoping is the mapping of the process. If this has not been done properly it is impossible to set boundaries and to keep a good overview in the inventory analysis, which in turn jeopardizes the impact and improvement assessments. The functional unit is the measure in which the final reporting will be brought out.

In the inventory analysis, all the energy and raw material flowing through the system boundaries are listed. In this analysis the laws of conservation of energy and mass apply, so these figures have to be consistent. The output of this inventory analysis has to be the functional unit. Hence, the carbon inflows as well as outflow will be examined in this section.

Subsequently, in the impact assessment, implications are coupled to the results of the inventory analysis. For example, the environmental impacts or resource depletion can be examined, using the data from the previous section.
In addition to this rather technical approach to the Life Cycle of pellet heat, a policy analysis will be made. This analysis will start by listing legislation and initiatives regarding pellet burning. As these initiatives will be considered part of the inventory, the listing will be done in the Inventory Analysis chapter.

Finally, based upon the findings in the impact assessment, the Conclusion and Discussion chapters describe conclusions and recommendations. These recommendations may involve improvements or changes in processes in the cycle.

3 Goal definition and scoping

The goal of this life-cycle analysis is to assess the carbon neutrality of pellet-burning technologies for domestic application. Therefore, the functional unit is grams CO₂ emitted/MJ. This can be a positive number, which implies a net carbon emission or a negative number, which corresponds to an overall C absorption.

The scope of this research will be limited to the following processes: Carbon sequestration during the growth of a tree, the transportation and processing of a tree into pellets and the combustion of wood pellets. More specific, the different parts of the tree are studied with respect to carbon sequestration and also forestry practices are looked into. Also, sound assumptions are made with regards to the parts of the tree usable for pelletizing and with respect to biomass yield of certain forest types. In the analysis of the logistics, pelletizing methodology will be emphasized and a distinction is made between domestic transportation and international transportation. In the paragraphs on the combustion of the tree, common household stoves and furnaces are examined in order to gain insight into the opportunities of wood pellets as a heating fuel with regards to mitigating the Green House Effect and enhancing air quality.

The research question and sub questions are:

- What is the net CO₂ emission of pellet appliances?
- What is the carbon absorption capacity of the trees used?
- What are the emissions of the pellets used during combustion?
- Where are the biggest inefficiencies in the cycle?
  - Where in the cycle does the bulk of C emissions occur?
- How can these inefficiencies be improved?
- What is driving these C output points?
- What is the influence of transportation of pellets on the cumulative C emissions across the cycle?
  - In Domestic transportation?
  - In International transportation?

Additionally, this work emphasizes the legal, political and societal aspects of the cycle. A summary (as opposed to a LCA) is made with respect to these aspects. The research questions with respect to these aspects will be of a different type as in the LCA. The research question regarding the societal aspects are:

- What is the government policy towards biomass as a heating fuel in the US?
- How does public policy influence innovation in wood burning technology?

4 Inventory analysis

4.1 The Carbon Inventory

The cycle starts with the process of growing a tree. When a tree grows, it takes in carbon dioxide (CO₂) through photosynthesis. The carbon taken in during this process is allocated in different parts of the tree. When focusing on carbon absorption, there are several important considerations and variables; forest productivity and therefore carbon absorption depends largely on tree species and forest management. The general phenomena, however, are similar for all types of trees and all types of forest management, as will become clear later.

When the total carbon uptake is calculated, the logistics of wood burning technologies are addressed: the tree has to be harvested, transported to a sawmill, dust is transported to the pellet factory and the pellets have to be produced and delivered to point of use.

The pellets are transported, either regionally or internationally to retailers, distributed locally and are eventually combusted in a pellet-burning device.

Figure 1: Aboveground tree biomass carbon content over time, assuming no harvest.
Source: Marland & Marland (1992)
The scope of this paper will be limited to the combustion of pellets for domestic heat and restricted to pellet-fueled applications, rather than wood chips. In the following paragraphs, all these processes will be described in order to establish a complete and extensive inventory analysis.

4.1.1 Carbon sequestration by trees

When looking at the ability of trees to absorb carbon dioxide, a few phenomena must be examined. The first interesting phenomenon is the allocation of carbon through the tree. Carbon absorption takes place in the leaves where photosynthesis occurs. From there, the carbon is moved throughout the tree and stored in different parts of the ecosystem. Niu & Duiker (2006) suggest there are four places in a living ecosystem where the carbon is allocated: the aboveground tree mass, the root biomass, forest floor litter and soil organic carbon. The following chapter describes these elements and ends with the implications this has if one would grow trees on a plantation. Then, the amount of carbon sequestered will be related to the amount of biomass accumulated, which eventually can be used as fuel in pellet stoves.

4.1.1.1 Aboveground tree biomass

In order to calculate the aboveground tree biomass, we use a model developed by Marland & Marland (1992). In their model, the assumption is made that the total sequestered carbon grows linearly until half of the maximum carbon sequestered. From there the accumulated carbon grows asymptotically to the maximum value. A graph of the model is displayed in figure 1.

This graph features the main characteristics on tree growth; it is observed that old trees do not sequester much carbon, whereas young forests have the highest sequestration rates. The values for growth rates varying between 1 Mg C/ha.yr and 3 Mg C/ha.yr, are achieved by young commercial forests in the United States and values near 10 Mg C/ha.yr by managed stands in the tropics (Marland & Marland (1992)). Growth rates mainly depend on tree species, stand age, the climate the forest is in and forest management. Chapter 4.1.1.7 discusses the amount of usable, sustainably harvested wood.

4.1.1.2 The root biomass

Niu & Duiker (2006) suggest that carbon uptake in the root biomass can be estimated as a function of the total aboveground biomass growth, a root/shoot ration and a rate of decay after harvesting. The exact contribution of root biomass is complex to determine. Niu & Duiker conclude, however, that the contribution of root biomass to carbon sequestration is equal to the contributions of Forest floor litter and soil organic carbon. This simplification is used throughout the upcoming chapters.

4.1.1.3 Forest floor litter

To calculate the carbon stored in the forest floor, Niu & Duiker employ a model, inspired by earlier work by Smith & Heath (2002). The model Smith & Heath model assumes a carbon growth and a natural decay of forest floor carbon after afforestation or reforestation. The carbon stored on the forest floor can be contained in nonliving plants or materials as leaves, twigs and woody stems, all of which are subject to decay. The net carbon growth can be obtained by deducting the decay from the growth. Niu & Duiker used this to examine the implications for forests and their results are displayed in figure 2. Figure 2A describes the Carbon storage for permanent forestation and Figure 2B describes the curve for a short-rotation cycle. Forest management will be elaborated later in this chapter. The typical amount of carbon stored in forest floor litter is about one ninth of the amount stored in aboveground biomass.

4.1.1.4 Soil organic carbon pool

In their article, Niu & Duiker have summarized literature in order to develop a model for the amount of carbon stored in soils. Soils appear to be able to act as carbon sinks and the rates for the first ten years after afforestation amount to 0.7 Mg/ha.yr. This rate declines however, and after 40 years, only 0.06 Mg/ha.yr has been taken up.

4.1.1.5 Overall carbon uptake by trees

Although exact figures on growth rates depend on the tree species, the phenomena of the total carbon absorption in trees are comparable for different species (Dewar & Canell, 1992). The total carbon stock is represented for a short rotation plantation of poplar by the solid line in figure 3. On the X-axis, the time is displayed in years, since the planting of the forest. The Y-axis represents the carbon storage in Mg C/ha. The steep declines in the first curve represent a harvest of the forest.

From these curves, a few conclusions can be derived that will be used in the further chapters. From the first curve, one can tell that in every subsequent harvest rotation, the carbon stock in trees accumulates linearly and starts over at
zero when a new rotation begins. Therefore, one can conclude that at this point that carbon is being harvested, after which the tree can be utilized for different purposes.

The assumption that the production of wood pellets is the only purpose for growing wood is used in the course of this research. This assumption is inaccurate. In reality, the wood used for pellets is sawdust, and is a residual from sawmills. Nonetheless, as the purpose of this paper is to assess the carbon impacts of pellets as heating fuel, this assumption will be made. After all, this assumption is useful in the calculation on the carbon balance of wood pellets in which other products are not considered. Hence, the second graph, that describes the carbon contained in wood products, such as like wood used for construction, is ignored.

From the third curve then, one can conclude that only the first three rotations contribute to a net Carbon absorption by the soil and litter and as of the fourth cycle, no contribution is being made. Thus one can conclude that as of cycle four, the only net carbon contribution is made in the aboveground tree biomass. This view is also supported by Yemashnov & McKenny (2009); they describe that carbon is being harvested in the form of a tree after a cycle, while some carbon is left in the ecosystem. This view is displayed in graph 3d. According to a literature review done by the Environmental Protection Agency, the typical carbon sequestration rate for reforested land is 0.7 – 5.0 Mg C/ha.yr.

The model described in the latter paragraphs however, only describes the carbon balance for trees, grown on plantations. Marland & Marland (1992) conclude that the most effective strategy to minimize increases in atmospheric CO₂ (and maximize the CO₂ stored in the forest) depends on the current status of the land. For land with high standing biomass and low productivity, they suggest that the most effective strategy would be to protect the standing stock. For land with little standing biomass and low productivity, the most beneficial strategy in terms of Carbon sequestration would be reforestation and ongoing management of the forest. For lands where high productivity can be expected, the most effective strategy is to manage the forest for a harvestable crop, in order to use this crop efficiently.

4.1.1.6 Relation to biomass yield

With the insight gained in the mechanisms of carbon sequestration, a relationship must be established with the implications of the CO₂ balance of the forest and the amount of harvestable wood to be used in wood burning devices. In the upcoming chapters, these steps will be discussed.

First, the amount of Carbon must be related to the amount of CO₂ sequestered in the system. This can be done by the simple calculation of the fraction of C in the CO₂ molecule. The element Carbon represents 12/44 of the total weight of the CO₂ molecule, and hence, the amount of CO₂ sequestered is obtained by multiplying the total amount of C taken up by the system by 44/12. This calculation uses the assumption that carbon dioxide is a forest’s only source of carbon.

As the purpose of this paper is to examine the relation between CO₂ absorption and the amount of wood obtained, the amount of C (or CO₂) sequestered must be related to the average wood yield of the forest. In literature, this average yield is often referred to as Yield Class, and is expressed in m³ wood/ha.yr. The value for this Yield Class depends mainly on tree species and the spacing of the trees. Typical values for Yield Classes vary between 6 and 24 m³/ha.yr (Dewar & Canell, 1992). Note that this Yield Class is not necessarily the amount of wood available for harvesting each year. For reasons concerning sustainability of the forest, the amount of harvestable wood is different from this value, as will be shown in section 4.1.1.7.

To come from a yield to a value for the net carbon uptake and a value for the weight of the wood yielded by the plantation, two more values have to be obtained: a value for the percentage of C in dry biomass and a density of the stem wood.

In order to derive a relationship between the yearly carbon yield and the yearly biomass yield, the following relation (Dewar & Canell, 1992) is used:

\[ \text{Carbon} = \text{Volume} \times d \times f_c \]

Where Volume represents the total volume accumulated by the tree, d represents the density in kg/m³ and \( f_c \) represents the fraction of carbon in the dry biomass. Multiplying both sides by \( \text{ha}^{-1} \times \text{yr}^{-1} \), leads to:

\[ \frac{\text{Carbon}}{\text{ha} \times \text{yr}} = \frac{\text{Volume}}{\text{ha} \times \text{yr}} \times d \times f_c \]

![Figure 4a, 3b, 3c, 3d: Overall carbon uptake over time by trees (a), carbon stored over time in long lived products (b), carbon stored over time in litter and soil (c) and the total carbon stored in all categories (d), all assuming a 20 year rotation cycle. Source: Dewar & Canell (1992)](image)
Where Volume/ha*yr is referred to as the Yield Class. The only figures that lack now are the density of the used wood and the fraction of carbon is this wood. Lamplom & Savidge (2003) describe Carbon fractions of different tree species, concluding that percentages for hardwood range between 46.27% and 49.97% and range from 47.21 to 55.2% in softwood.

From this relation, a formula can be derived for the total biomass obtained in a given time span by:

\[
\frac{\text{Carbon}}{\text{ha*yr}} = \frac{1}{f_c} \cdot \frac{\text{Volume}}{\text{ha*yr}} \cdot d
\]

When we gained more insight into the phenomena regarding carbon absorption by trees, these theories can be put into perspective of forest management. From these forest management practices, a figure should be obtained for the harvestable amount of biomass per year.

### 4.1.1.7 Sustainably harvested wood

The latter paragraphs describe a rather theoretical approach to the productivity of a forest. In real life application, more aspects have to be taken into consideration than the annual growth of a forest to calculate the annual sustainable harvest. Many reports are currently in the making, or have just been released. The most recent one is the Manomet Biomass Sustainability and Carbon Policy Study (2010), for the state of Massachusetts.

To obtain the typical curve as displayed in figure 3, guidelines have to be taken into consideration in order to maintain a sustainable growth. The debate about what percentage of the standing biomass to harvest is ongoing in many states and controversial among policy makers and environmental protectionists nationwide. Nonetheless, scholars have researched these topics and defined guidelines for sustainable harvesting in some states. These guidelines focus on concerns about long-term site productivity, biodiversity, water quality and wildlife habitat alterations. These restrictions have been summarized in appendix A (courtesy Bill Stewart, University of Berkely, CA).

Even though it is beyond the scope of this research to go into the details of sustainable harvesting, it is important to make some calculations with regards to pellets. These calculations are simplified and are therefore not necessarily accurate. Rather, they give some feeling for the typical yield of a forest, if harvested sustainably. In this example, we take the guidelines for Pennsylvanian forests, as these are the easiest to work with. Also, they seem to be the most conservative from the chart in appendix A.

The guideline states that 15-30% of the preharvested biomass should be left in the forest, meaning that 1 in every 3 to 6 trees should be preserved. We know from previous sections that the production of a forest is between 0,7 and 5,0 Mg C/ha*yr (EPA) is from previous chapters, and the percentage of carbon in wood is assumed to be 50%. The amount of woody biomass yielded is therefore:

- **Minimum**: (0,7 Mg C/ha*yr) * (1/50%) * (1-30%) = 0,98 Mg wood/ha*yr
- **Maximum**: (5,0 Mg C/ha*yr) * (1/50%) * (1-15%) = 8,50 Mg wood/ha*yr

The sustainable wood harvest would be between 0,98 ton and 8,50 ton wood per hectare per year. As wood is usually harvested in rotations that last between 20 and 40 years, one hectare could yield:

- For a 20 year rotation, 'Minimum': (0,98 Mg wood/ha*yr) * 20 yr = 19,6 Mg wood/ha
- For a 40 year rotation, 'Minimum': (0,98 Mg wood/ha*yr) * 40 yr = 39,2 Mg wood/ha
- For a 20 year rotation, 'Maximum': (8,50 Mg wood/ha*yr) * 20 yr = 170,0 Mg wood/ha
- For a 40 year rotation, 'Maximum': (8,50 Mg wood/ha*yr) * 40 yr = 340,0 Mg wood/ha

### 4.1.2 Logistics of wood burning technologies

After the tree has grown, it has to be harvested, transported, processed into pellets and moved again, in order to reach the end-consumer. Few scholars have researched the impacts of these processes to the Carbon cycle, but Magelli et al. (2009) developed a model that describes the full path from harvesting to retailing. They describe both the CO₂ emissions and the energy consumption of pellets being consumed in Europe, originating in British Columbia, Canada. The data from this paper will be used as a basis for further calculation.

Figure 5 visualizes the cycle. The tree is harvested and moved 110 km to a lumber mill, where the tree is being converted into sawdust. From there, the raw material is transported to a pellet plant and processed into pellets. A train moves the pellets from the plant to the Vancouver harbor, from where the pellets are then shipped to the
Stockholm port in Sweden. In reality, pellets are mainly shipped to ports in the Netherlands, Belgium and Sweden, which are approximately equidistant from Stockholm (Magelli et al. (2009)). The calculations made for shipment overseas are highly relevant as Canada transports around 60% of its pellet production to destinations in Europe (Spelter & Toth, 2009).

4.1.2.1 Harvesting and wood residues’ production
In the paper, harvesting from natural forest is considered. Also, the impact of reforestation has not been taken into account. Nevertheless, the figures will give us a good insight in the energy consumed and the pollutants emitted. There has been calculated that the production of the equivalent of 1 ton pellets in sawdust corresponds the consumption of 0.53 GJ/ton.

4.1.2.2 Transportation to pellet plant
To calculate the energy consumed and the carbon exhausted, the assumption has been made that movement of pellets goes by truck, for which the energy consumption has been set on 1590 kJ/ton.km. The assumption is made that the sawdust travels 28 km in order to reach the pellet plant. In order to produce one ton of pellets, 1.56 ton of sawdust is being consumed. This contributes to 0.07 GJ/ton pellets produced.

4.1.2.3 Wood Pellet production
The processes involved in this step are the drying of the wood chips and compressing it into wood pellets. The article describes two ways of drying the pellets; by using natural gas as a heating fuel and using wet sawdust as heating fuel. The article considers wet sawdust as carbon neutral. As the scope of this research is to assess whether or not this is the case, this is disputable. This consideration however, has no implications for the energy consumed. The energy consumed accumulates to either 3.78 GJ/ton (sawdust) or 2.97 GJ/ton (natural gas).

4.1.2.4 Transportation by train
After the production of the pellets, a train moves them from the plant to the port. The energy consumption of the trains used is estimated at 0.336 MJ/ton.km. The total energy consumed on a 780 km train ride is 0.26 GJ/ton.

4.1.2.5 Transportation by vessel
As the pellets travel from Canada to Europe, the most efficient way of transportation is by vessel. The paper shows that this journey consumes 2.6 GJ/ton.

The contributions to the energy consumed in this logistic process and their contributions in terms of the most important pollutants have been listed in table 1. As the purpose of this paper is to assess the carbon neutrality of the cycle, only the compounds that contribute to a net carbon emission are listed. Besides these elements, small amounts of N2O, NOx, SOx and Particulate Matter (PM) are also emitted. It is however, beyond the scope of this research to examine these emissions.

<table>
<thead>
<tr>
<th>Energy and pollutant</th>
<th>Harvest</th>
<th>Truck</th>
<th>Production</th>
<th>Natural gas</th>
<th>Train</th>
<th>Ocean vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumed (GJ/ton)</td>
<td>0.58</td>
<td>0.07</td>
<td>3.78</td>
<td>2.97</td>
<td>0.26</td>
<td>2.6</td>
</tr>
<tr>
<td>CO2 (g/ton)</td>
<td>29850</td>
<td>4675</td>
<td>27800</td>
<td>193000</td>
<td>12785</td>
<td>206440</td>
</tr>
<tr>
<td>CO (g/ton)</td>
<td>494</td>
<td>26.5</td>
<td>222</td>
<td>239</td>
<td>33.6</td>
<td>420</td>
</tr>
<tr>
<td>CH4 (g/ton)</td>
<td>24.3</td>
<td>0.39</td>
<td>5.3</td>
<td>924</td>
<td>n.a.</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 1: Energy consumed and pollutants emitted during transatlantic transportation and manufacturing of wood pellets

As can be seen from the table, the largest contributors in this process are the production of pellets and the shipping of the pellets. In table 2 the totals are summarized. The carbon contribution has been determined by multiplying the total amount by the relative abundance in of carbon in the compound.

<table>
<thead>
<tr>
<th>Energy (GJ/t)</th>
<th>CO2 (g/t)</th>
<th>CO (g/t)</th>
<th>CH4 (g/t)</th>
<th>Total carbon (g/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total – Sawdust</td>
<td>7.29</td>
<td>281550</td>
<td>1196.1</td>
<td>77338.72</td>
</tr>
<tr>
<td>Total – Nat gas</td>
<td>6.48</td>
<td>446750</td>
<td>1213.1</td>
<td>123089.58</td>
</tr>
</tbody>
</table>

Table 2: Totals of energy and most abundant pollutants during transatlantic transportation and manufacturing of wood pellets

The next step is to calculate what the energy and carbon efficiencies are when the pellets are used on a local scale. Therefore, the train trip from the pellet plant to the port and the journey of the pellets on the vessel will be left out of the equation, for obvious reasons. These steps will be replaced by trip of 150 km by truck, which is a likely distance for these pellets to travel. The same emission characteristics apply as for the first ride. This will result in the figures as listed in table 3.
Table 3: Energy consumed and pollutants emitted during domestic transportation and manufacturing of wood pellets.

<table>
<thead>
<tr>
<th>Energy and pollutant</th>
<th>Harvest</th>
<th>Truck</th>
<th>Production</th>
<th>Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumed</td>
<td></td>
<td></td>
<td>Sawdust as fuel</td>
<td>Natural gas as fuel</td>
</tr>
<tr>
<td>(GJ/ton)</td>
<td>0,58</td>
<td>0,07</td>
<td>3,78</td>
<td>2,97</td>
</tr>
<tr>
<td>CO2 (g/ton)</td>
<td>29850</td>
<td>4675</td>
<td>27800</td>
<td>193000</td>
</tr>
<tr>
<td>CO (g/ton)</td>
<td>494</td>
<td>26,5</td>
<td>222</td>
<td>239</td>
</tr>
<tr>
<td>CH4 (g/ton)</td>
<td>24,3</td>
<td>0,39</td>
<td>5,3</td>
<td>924</td>
</tr>
</tbody>
</table>

Table 4: Totals of energy and most abundant pollutants during domestic transportation and manufacturing of wood pellets.

4.1.3 Stove Emissions

The section on tree growth showed that wood consists of about 50% carbon in dry biomass. If this Carbon burns completely, the following reaction occurs:

\[ C + O_2 \rightarrow CO_2 \]

However, tiny amounts of carbon will either burn incompletely, or, due to the complex molecular structure of wood, converted into complex molecules. The following section will be aimed at finding what percentage of the total carbon in wood will be converted into other compounds than CO2. As conservation laws apply, one acknowledgement has to be made however: All elemental carbon burned in an appliance will be converted to CO2 or other carbon products. The relative abundance in emission gasses may differ, as well as the efficiency en consequently the fuel consumption of the appliance.

According to a study by Kjallstad & Olsson (2004a), the most abundant compounds in chimney outlets from different forms of wood burning technologies are Carbon dioxide (CO2), Carbon monoxide (CO), Methane (CH4), Benzene (C6H6), Methoxyphenols and Pyrene. Even though the their paper represents the amounts emitted in mg/m3 and does not relate these amounts to the pellet input, we will use their figures to make some calculations. Additionally, some assumptions will be made, in favor of these calculations.

The results of the Kjallstad & Olsson study are summarized in table 5. They define two different pellet fueled appliances and their results are listed in mg/m3. Under the assumption that these compounds represent all the emissions, the relative abundance of the species are listed in the column on the right. The assumption that these emissions represent almost the whole of the particles emitted, is invigorated by the paper by Olsson & Kjallstad (2004b), which claims that Benzene represents 70% of the total amount of aromatic compounds released so this set of compounds can be considered a good representation. The big difference in absolute emissions can be explained by the size of the appliances. The 20 kW appliance uses more wood, so it gives more emissions than the 7 kW appliance. It is therefore much more interesting to examine the relative abundance of the compounds emitted.

Table 5: Emissions of a 20 kW pellet burner and a 7 kW pellet stove (Source: Kjallstad & Olsson (2004a))

<table>
<thead>
<tr>
<th>Pellet burner Emissions (mg/m3)</th>
<th>Relative (by weight)</th>
<th>Pellet stove Emissions (mg/m3)</th>
<th>Relative (by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>130000</td>
<td>99,990%</td>
<td>46000</td>
</tr>
<tr>
<td>CO</td>
<td>13</td>
<td>0,010%</td>
<td>610</td>
</tr>
<tr>
<td>CH4</td>
<td>0,3</td>
<td>0,000%</td>
<td>5</td>
</tr>
<tr>
<td>Benzene</td>
<td>0,01</td>
<td>0,000%</td>
<td>0,6</td>
</tr>
<tr>
<td>Methoxyphenol</td>
<td>0</td>
<td>0,000%</td>
<td>2</td>
</tr>
<tr>
<td>Pyrene</td>
<td>0</td>
<td>0,000%</td>
<td>0</td>
</tr>
</tbody>
</table>

The original paper indicates that these figures should be seen as examples, rather than representative for specific devices. Hence, as it is likely that these figures come close to the figures for a typical stove with indicated power outlets, these will be used for calculations with regards to carbon neutrality.

If we take these figures now as representative for a burning process in a pellet appliance, than that would mean that approximately 98-100% of the carbon emissions from the pellets, is being converted to CO2. Besides CO2, small fractions
of other compounds are created. In general, these other compounds have a larger impact on global warming and are more hazardous to human health. Therefore it is important to assess the relative conversion factors of these other compounds.

In order to calculate what this means for the total combustion of a ton of pellets, there has been calculated what percentage of elemental carbon is converted to which compound. For this purpose, the relative abundance of Carbon in each compound was calculated and this figure was multiplied by the weight of the corresponding compound in the total emission to obtain the total Carbon abundance in each individual emitted species. From there, it is relatively easy to calculate the relative allocation of the elemental carbon. In table 6 the results of these calculations have been listed for the 7 kW pellet stove.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Absolute emission (mg/m3)</th>
<th>Relative C abundance in compound (%)</th>
<th>Total C abundance in compound (mg/m3)</th>
<th>Relative C of total C per compound (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>46000</td>
<td>27.27%</td>
<td>12545,45</td>
<td>97,92%</td>
</tr>
<tr>
<td>CO</td>
<td>610</td>
<td>42.86%</td>
<td>261,43</td>
<td>2,04%</td>
</tr>
<tr>
<td>CH₄</td>
<td>5</td>
<td>75.00%</td>
<td>3,75</td>
<td>0,03%</td>
</tr>
<tr>
<td>Benzene</td>
<td>0,6</td>
<td>92.31%</td>
<td>0,55</td>
<td>0,00%</td>
</tr>
<tr>
<td>Methoxyphenol</td>
<td>2</td>
<td>67.74%</td>
<td>1,35</td>
<td>0,01%</td>
</tr>
<tr>
<td>Pyrene</td>
<td>0</td>
<td>95.05%</td>
<td>0,00</td>
<td>0,00%</td>
</tr>
</tbody>
</table>

Table 6: Relative Carbon content of different emitted compounds, calculated for the 7 kW pellet stove

From this, we can deduce that approximately 98% of the carbon contained in the wood, is burned to CO₂ and around 2% is converted to CO in the 7kW pellet stove.

Now we return to what this means for a ton of wood pellets. Therefore, another assumption needs introduction: A decision has to be made on the tree species. As the calculations for the export cycle are based on trees grown in British Columbia, Canada, it is useful to base our calculations on a type of wood that is grown there. Therefore, we assume that this ton of wood consists for 100% of coniferous softwood with an average carbon percentage of 51.2% (actual rates are between 47.21 and 55.2%, Lamлом & Savidge, 2003). An important note herein is that we speak of dry tons. The figures of the transportation cycle have been adjusted for dry and wet wood. Thus, the carbon content of this ton of the dry wood is:

$$1000 \text{kg} \times 51.2\% = 512 \text{kg}$$

As CO₂ contains a 12/44 share of Carbon by weight, the tree has, in order to form this ton of wood, sequestered:

$$512 \text{ kg C} \times \frac{44}{12} = 1,877.33 \text{ kg CO}_2$$

Now, we assume that the full bunch of wood will be converted into pellets. This is not likely, but as the purpose of this paper is to assess the carbon neutrality of wood pellets, it does not make sense to take other products into consideration. The wood in this context is only the harvested wood and not the full amount of grown forest. The latter may be higher due to restrictions with regards to sustainable harvesting, as has been discussed in 4.1.1.7.

As 512 kg C corresponds to 42666.7 mol elemental C/ton wood, we can now calculate how many moles of the other compounds are being formed while combusting a pellets in an appliance. Again, the calculations for the 7 kW wood stove are displayed in the table 7. Please note that for Benzene, Methoxyphenol and Pyrene the total amount of moles Carbon has to be divided by the number of C atoms in these elements in order to obtain the correct figure.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Emissions in grams/ton pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1,838,200,32</td>
</tr>
<tr>
<td>CO</td>
<td>24,376,13</td>
</tr>
<tr>
<td>CH₄</td>
<td>199,80</td>
</tr>
<tr>
<td>Benzene</td>
<td>23,98</td>
</tr>
<tr>
<td>Methoxyphenol</td>
<td>79,92</td>
</tr>
<tr>
<td>Pyrene</td>
<td>0,00</td>
</tr>
</tbody>
</table>

Table 7: Grams of compound formed from 1 ton of pellets in the 7 kW pellet stove

If we now sum all these contributions both from the logistic processes and the emissions from combustion, the total carbon emissions yield:
4.1.4 The Balance

Under the assumptions made in the previous sections, the carbon cycle can be summarized as follows: An ecosystem takes up carbon, where effectively the carbon sequestered in the aboveground biomass is being harvested and used. Some carbon is being left in the forest floors and will stay there during the subsequent harvest cycles. The amount of Carbon taken up and the amount of carbon left in soils is dependent on tree species and forest management. Nevertheless, the phenomena involved are the same for every type of tree and to calculate the balance, the type of tree is not relevant, as this will only influence the exact rates and figures and not the phenomena.

Then, the logistic cycle starts. The assumption will be made that this cycle is the same for every type of tree used. In the logistic processes, two decisions are crucial: the pellets can be manufactured using sawdust as a drying fuel or natural gas. Additionally, the pellets can be used domestically or used for export.

Finally, the pellets can be burned in two different appliances. These appliances have different characteristics with regards to emitted gases and are hence to a more or lesser extent polluting. In the following section, calculations with regards to the carbon balance will be discussed.

4.1.4.1 Calculations

In this chapter, the emissions that appear through the process of the manufacturing and combustion of pellets are summarized and compared with the theoretical minimum carbon uptake for a forest to produce a certain amount of pellets.

In the previous chapters, we have obtained figures for the emissions through the processes. To assess the total carbon balance, one must distract the amount of CO$_2$ sequestered from the amount of CO$_2$ emitted. The amount CO$_2$ sequestered can easily be obtained by using the earlier made assumption that the source of all Carbon stored in the wood is CO$_2$ from the atmosphere. Therefore, the 1877,33 kg CO$_2$/ton pellets from the latter chapter is used again to distract from the total CO$_2$ emission.

And if we distract the total CO$_2$ sequestered by the tree from the total CO$_2$ emitted, the following balance occurs (amounts in grams/ton pellets):

<table>
<thead>
<tr>
<th></th>
<th>Export-Sawdust</th>
<th>Export-Nat. gas</th>
<th>Domestic-Sawdust</th>
<th>Domestic-Nat. gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>305.748,35</td>
<td>470.948,35</td>
<td>102.723,35</td>
<td>267.923,35</td>
</tr>
<tr>
<td>CO</td>
<td>25.572,23</td>
<td>25.589,23</td>
<td>25.210,13</td>
<td>25.326,17</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>252,79</td>
<td>1.171,49</td>
<td>231,14</td>
<td>1.149,84</td>
</tr>
<tr>
<td>Benzene</td>
<td>143,86</td>
<td>143,86</td>
<td>143,86</td>
<td>143,86</td>
</tr>
<tr>
<td>Methoxyphenol</td>
<td>559,45</td>
<td>559,45</td>
<td>559,45</td>
<td>559,45</td>
</tr>
<tr>
<td>Pyrene</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
</tbody>
</table>

Table 9: Total emissions from manufacturing, transportation and combustion, minus the CO$_2$ sequestered during the growth of the forest, calculated for the equivalent of 1 ton of wood pellets, for the 7 kW pellet stove

As could have been expected, the pellets for domestic usage, dried with sawdust as a heating fuel, have the lowest carbon emissions, whereas the exported pellets, dried with natural gas, have the highest carbon impact.

The same calculations can be made for the measurements, also done by Kjallstad & Olsson (2004a), of a 20 kW pellet burner. This burner was connected to a water tank and the system served as a boiler. The total emissions of this device, including the emissions obtained in the logistic processes are listed in table 10 (amounts in grams/ton pellets).
Greenhouse gases, and are therefore not considered to have impact on global warming. Methane, with a GWP of 21, is the other Green House Gas emitted in this type of appliances and is by the amount of emissions taken does not provide a value. In literature, these values vary from 15-18 MJ/kg and European standards require values of at least 15.9 MJ/kg (DIN-51731) up to 18 MJ/kg (DINplus, O-Norm M-7135), (Verma et al. 2009). Therefore, in these calculations, 17 MJ/kg is the chosen value. With this caloric value for the pellets used, the emissions for the 20 kW pellet burner, per MJ amount to (values in g/MJ):

<table>
<thead>
<tr>
<th></th>
<th>Export-Sawdust</th>
<th>Export-Nat. gas</th>
<th>Domestic-Sawdust</th>
<th>Domestic-Nat. gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>20,27</td>
<td>29,99</td>
<td>8,33</td>
<td>18,04</td>
</tr>
<tr>
<td>CO</td>
<td>0,08</td>
<td>0,08</td>
<td>0,06</td>
<td>0,07</td>
</tr>
<tr>
<td>CH₄</td>
<td>0,00</td>
<td>0,06</td>
<td>0,00</td>
<td>0,06</td>
</tr>
<tr>
<td>Benzene</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
<tr>
<td>Methoxyphenol</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
<tr>
<td>Pyrene</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
</tbody>
</table>

Table 10: Total emissions from manufacturing, transportation and combustion, minus the CO₂ sequestered during the growth of the forest, calculated for the equivalent of 1 ton of wood pellets, for the 20 kW pellet burner

5 Impact Assessment

Now we know which emissions occur and in what quantities, one can calculate which implications this has in terms of the Green House Effect and on air quality. Also, a comparison can be made with other forms of renewable energy and with fossil fuels.

These amounts must be converted into [g]/[kW]. This makes comparison with other fuels easier and more appropriate. In order to convert the units from [g emission]/[kg pellets], another assumption has to be introduced. A value has to be chosen for the calorific content of the pellets as the literature from which these values were taken does not provide a certain mode of application, heating oil and natural gas emit 100,1 g CO₂/MJ and 62,8 g CO₂/MJ respectively. Their research does not emphasize the other compounds emitted, so the only means of comparing the fuels is by the amount of CO₂ they emit.

In order to complete the assessment of wood pellets as a heating fuel, one can look into the impacts on the Green House Effect. As the GHE is caused by a wide variety of gases, all with different impacts, scale factors will have to be used. A well-known set of scale factors are the values of the Global Warming Potential. The GWP values, as set by the Intergovernmental Panel on Climate Change (IPCC), are measures for the impact of a certain gas to the Green House Effect. The Greenhouse Gas CO₂ has a value of 1, and the other Green House Gas emitted in this type of appliances is Methane, with a GWP of 21 (for a 100 year time horizon). The other emitted gases are not on the IPCC list of Greenhouse gases, and are therefore not considered to have impact on global warming.

<table>
<thead>
<tr>
<th></th>
<th>Export-Sawdust</th>
<th>Export-Nat. gas</th>
<th>Domestic-Sawdust</th>
<th>Domestic-Nat. gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>17,99</td>
<td>27,70</td>
<td>6,04</td>
<td>15,76</td>
</tr>
<tr>
<td>CO</td>
<td>1,50</td>
<td>1,51</td>
<td>1,48</td>
<td>1,49</td>
</tr>
<tr>
<td>CH₄</td>
<td>0,01</td>
<td>0,07</td>
<td>0,01</td>
<td>0,07</td>
</tr>
<tr>
<td>Benzene</td>
<td>0,01</td>
<td>0,01</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td>Methoxyphenol</td>
<td>0,03</td>
<td>0,03</td>
<td>0,03</td>
<td>0,03</td>
</tr>
<tr>
<td>Pyrene</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
</tbody>
</table>

Table 11: Emissions of the 20 kW pellet burner, values in [g]/[MJ]

For the 7 kW pellet stove these emissions amount to:

<table>
<thead>
<tr>
<th></th>
<th>Export-Sawdust</th>
<th>Export-Nat. gas</th>
<th>Domestic-Sawdust</th>
<th>Domestic-Nat. gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>17,99</td>
<td>27,70</td>
<td>6,04</td>
<td>15,76</td>
</tr>
<tr>
<td>CO</td>
<td>1,50</td>
<td>1,51</td>
<td>1,48</td>
<td>1,49</td>
</tr>
<tr>
<td>CH₄</td>
<td>0,01</td>
<td>0,07</td>
<td>0,01</td>
<td>0,07</td>
</tr>
<tr>
<td>Benzene</td>
<td>0,01</td>
<td>0,01</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td>Methoxyphenol</td>
<td>0,03</td>
<td>0,03</td>
<td>0,03</td>
<td>0,03</td>
</tr>
<tr>
<td>Pyrene</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
</tbody>
</table>

Table 12: Emissions of the 7 kW pellet stove, values in [g]/[MJ]

These values allow us to make a comparison with other heating fuels. The most widely used fuels for heating are heating oil and natural gas.

It is beyond the scope of this research to assess the full life cycle of these other heating fuels. However, the University of Wisconsin, in cooperation with Futuremetrics (2007) has conducted such a life cycle analysis. Their conclusion is that, in their most efficient mode of application, heating oil and natural gas emit 100,1 g CO₂/MJ and 62,8 g CO₂/MJ respectively. Their research does not emphasize the other compounds emitted, so the only means of comparing the fuels is by the amount of CO₂ they emit.

In order to complete the assessment of wood pellets as a heating fuel, one can look into the impacts on the Green House Effect. As the GHE is caused by a wide variety of gases, all with different impacts, scale factors will have to be used. A well-known set of scale factors are the values of the Global Warming Potential. The GWP values, as set by the Intergovernmental Panel on Climate Change (IPCC), are measures for the impact of a certain gas to the Green House Effect. The Greenhouse Gas CO₂ has a value of 1, and the other Green House Gas emitted in this type of appliances is Methane, with a GWP of 21 (for a 100 year time horizon). The other emitted gases are not on the IPCC list of Greenhouse gases, and are therefore not considered to have impact on global warming.
6 Policy on pellet heat

This section analyzes federal and state level policies regarding the use of wood pellets in domestic appliances. Most regulations are based on the Farm Bill, the Clean Air Act and the American Recovery and Reinvestment Act (ARRA).

President Obama signed the ARRA into law on February 17, 2009, in direct response to the economic crisis. The act aims to create new jobs, save existing ones and spur the economy by investing in long-term growth and by issuing various tax credits, loans and grants. The Recovery Act is also targeted at infrastructure development and enhancement; the Act plans investment in the domestic renewable energy industry and the weatherizing of 75 percent of federal buildings as well as more than one million private homes around the country.

The Farm Bill, also known as The Food, Conservation, and Energy Act of 2008, signed into law in June 2008, will govern the bulk of Federal agriculture and related programs for the next 5 years. Its 15 titles include administrative and funding authorities for programs that cover income and commodity price support, farm credit, and risk management; conservation though land retirement, stewardship of land and water resources, and farmland protection; food assistance and agricultural development efforts abroad and promotion of international access to American farm products; food stamps, domestic food distribution, and nutrition initiatives; rural community and economic development initiatives, including regional development, rural energy efficiency, water and waste facilities, and access to broadband technology; research on critical areas of the agricultural and food sector; accessibility and sustainability of forests; encouraging production and use of agricultural and rural renewable energy sources; and initiatives for attracting and retaining beginning and socially disadvantaged farmers and ranchers.

The Clean Air Act is the law that defines EPA’s (Environmental Protection Agency) responsibilities for protecting and improving the air quality and the stratospheric ozone layer for the US. Congress enacted the last major change in the law, the Clean Air Act Amendments of 1990, in 1990. Legislation passed since then has made several minor changes.

The most predominant institutions in charge of enforcing these laws are the US Department of Agriculture (USDA), the Department of Energy (DOE) and the Environmental Protection Agency (EPA).

It is important to acknowledge that mostly the federal policies are taken into account in this paper. A few examples of state or county level regulations will be described also. The states where these apply are indicated where appropriate.

Analysis takes place in two parts: the effects of policy on innovation in the wood pellet sector are stressed and the effects on the carbon balance are emphasized.

This policy analysis emphasizes the activities of the US federal government regarding pellet heat and the role of these actions in the System of Innovation approach. First, the theory of Systems of Innovation is described, after which legislation regarding pellets as a heating fuel will be listed. Then, the theory is applied to the legislation and this will lead to a conclusion and discussion about what role the US government plays in this System of Innovation.

6.1 Introduction to Systems of Innovation

When considering innovation, a distinction is made between product and process innovation. Product innovation involves the innovation of a tangible, such as new materials or a new design of a product. Process innovation regards an innovation in, for example, producing or organizing. Companies, however, often innovate in both fields and a new product are often accompanied new services or new legislation.

Also, firms often operate in networks and in constant interaction with their environment. Factors influencing innovation stretch therefore often far outside the organization and this network can be described as a System of Innovation.

In this paper National Systems of Innovation are emphasized. Freeman (1987) introduces the term National Systems of Innovation and defines it as

"The network of institutions in the public and private sectors whose activities and interactions initiate, import and diffuse new technologies."

Edquist (1997) uses a broader definition and defines it as

"All important economic, social, political, organizational, industrial and other factors that influence the development, diffusion and use of innovation."

Both definitions are still rather broad and abstract. Edquist (2006) takes another perspective and argues that a System of Innovation can be described in two ways: by describing its constituents and by describing the actions and relations between these constituents. These constituents can be organizations and institutions. Organizations are defined as formal structures, consciously created, have an explicit purpose and act in the systems of innovation. Examples of organizations can be firms, but also universities and research centers or venture capitalists. Institutions are defined as sets of common habits, rules, laws and regulations. In a way, they form the boundaries that organizations have to obey.

In these complex networks, all these bodies engage in certain activities. These activities may involve various matters among scholars, there is no consensus as to which activities should be considered when considering a System of
Innovation. Some focus on actions that are needed to convert an idea into a new product or process and others put the accent on the creation, transfer and exploitation of knowledge.

Edquist (2006) develops a list of activities that both organizations and institutions may undertake that influence the National System of Innovation. Table 13 displays this list that is based on earlier literature. Although arbitrary, this paper uses Edquist’s list to assess the role of the US government in this System of Innovation. More specifically, the role of the government as an institution is examined with respect to System of Innovation of pellet burning technologies. The reason for using this model is that it stresses both the knowledge-side as the market-side activities.

I. Provision of knowledge inputs to the innovation process
1. Provision of R&D and, thus, creating new knowledge, primarily in engineering, medicine and natural sciences.
2. Competence building: educating and training the labor force for innovation and R&D activities.

II. Demand-side activities
4. Articulation of quality requirements emanating from the demand side with regard to new products.

III. Provision of constituents for SI’s
5. Creating and changing organizations needed for developing new fields of innovation. Examples include enhancing entrepreneurship to create new firms and intrapreneurship to diversify existing firms; and creating new research organizations, policy agencies, and so on.
6. Networking through markets and other mechanisms, including interactive learning between different organizations (potentially) involved in innovation processes. This implies integrating new knowledge elements, developed in different spheres of the SI and coming from outside, with elements already available in the innovating firms.
7. Creating and changing institutions – e.g., patent laws, tax laws, environment and safety regulations, R&D investment routines, etc. – that influence innovating organizations and innovation processes by providing incentives for and removing obstacles to innovation.

IV. Support services for innovating firms
8. Incubating activities such as providing access to facilities and administrative support for innovating efforts.
9. Financing of innovation processes and other activities that can facilitate commercialization of knowledge and its adoption.
10. Provision of consultancy services of relevance for innovation processes, e.g., technology transfer, commercial information, and legal advice.

Table 13: List of possible activities in a System of Innovation (Edquist 2006)

Organizations and institutions can execute both activities, although certain tasks are more appropriate for one of the two. In his paper, Edquist discusses the role that a government should take in this framework. The purpose of this paper, however, is not to decide which tasks should be carried out by the government, and uses this model therefore in a purely analytical way and more as a tool to assess the role of the government in this SI.

With this explanation in mind, we continue with an overview of the initiatives as initiated by the US government with regards to biomass as a heating fuel.

6.2 Initiatives

The US government has a few programs in force with respect to regulation and promotion of the use of biomass as a heating fuel. The most important instruments the US government has are the Environmental Protection Agency (EPA), the US Department of Agriculture (USDA) and the Department of Energy (DOE). The following section will give a description of the programs initiated by these government bodies.

6.2.1 Biomass Research & Development

This part of the Farm Bill extends the Biomass Research and Development Act of 2000 and states that the Department of Agriculture and the Department of Energy should participate in joint projects regarding R&D of biomass. The act created the Biomass Research and Development Initiative. It also established the Biomass Research and Development Board and the Biomass R&D Technical Advisory Committee, which coordinate and accelerate all Federal biobased products and bioenergy research and development.

6.2.2 Environmental Protection Agency: Regulation of Emissions

In 1988, the EPA has set emission limits for biomass stoves to restrict emissions of particulate matter. The limits for this type of emissions are 7.5 grams/hour for noncatalytic wood stoves and 4.1 grams/hour for catalytic stoves. In addition to that, the EPA has assembled a list of certified wood heating appliances that have been tested in accredited laboratories for particulate emissions.
This list of certified wood burning appliances is a result of the Standard for New Residential Wood Heaters under the Clean Air Act.
The certification of an appliance has advantages in some states; appliances may be eligible for incentive programs when they qualify for this certification.

### 6.2.3 IRS: Tax credit for biomass appliance

Certain biomass appliances for domestic heating qualify for this program. In 2009 and 2010, a tax credit of 30% of the purchase costs of efficient biomass appliances is available. A maximum of $1500 applies. The stove has to reach an efficiency of at least 75% and must be installed in the owner’s primary residence.

This tax credit is part of the American Recovery and Reinvestment Act (ARRA).

### 6.2.4 US Department of Agriculture: Biomass Crop Assistance Program

The Biomass Crop Assistance Program (BCAP) provides financial support for producers of eligible biomass for heat, power, biobased products or biofuels. Support is issued for the collection, harvest, storage and transportation involved in the biomass delivery.

This program mainly caters to agricultural and forest landowners and supports them in the aforementioned activities. The subsidy is a matching payment. This means that USDA subsidizes every dollar an agricultural firm gets for the manufacturing and delivering of their biomass, with another dollar. The subsidy has a minimum of $1/ton eligible biomass and a maximum of $45/ton and a maximum duration of 2 years. In fiscal years 2009 and 2010, $5.1 million was awarded for the production of wood pellets and $11.2 million for sawdust. Discussion is still ongoing about whether or not to include biomass intended for export.

### 6.2.5 Forest Biomass for Energy

This program provides a yearly $15 million budget to spend on conducting a competitive research and development program encouraging the use of forest biomass for energy. The Forest Service shall conduct this research. Possible directions for research may include the development of technology and techniques to use low-value forest biomass, such as byproducts of forest health treatments and hazardous fuels reduction for the production of energy. Also the further development of existing manufacturing streams and the development of new transportation fuels from forest biomass are possible topics of study. Another topic covered by this program is the improvement of the growth and the yield of trees intended for renewable energy production.

### 6.2.6 Department of Energy: PACE Loans

Approximately $80 million has been made available under the State Energy Program for the DOE to spend in Property Assessed Clean Energy (PACE) programs. These programs allow homeowners to attach the full amount of their investment in an appliance for clean energy, to their property tax bill. This gives them the opportunity to repay the investment over a period of up to 20 to 40 years.

A big advantage of this type of program is that as the repayment appears on the property tax bill, the repayment is being transferred with your property, in case it is sold. Another advantage is that the applicant for a PACE loan has no or very low upfront costs.

### 6.2.7 Environmental Protection Agency: Burn Wise

Burn Wise is an initiative of the EPA that covers education and outreach programs in regard to wood combustion. Its main focus is to form partnerships with local agencies to inform communities on how to bring the cleanest appliances to the market and how to use appliances in the cleanest way.

The Burn Wise website provides information for consumers who consider heating with wood, as well as information for corporations involved in wood heating.

### 6.3 Effects of Policies

#### 6.3.1 The role of the government in the System of Innovation

Table 14 displays the different types of initiatives and assigns the activities to these types. The numbers 1 through 10 on the vertical direction represent the initiatives as displayed in table 14. In the horizontal direction, the initiatives are displayed.
how forests can become more productive. These two get funds to find out more on sustainable harvesting and efforts to grow and sell eligible biomass, whereas scientists policies have been categorized and attached to the different parts It is hard to tell what the exact influence of 6.3.2 Into biofuels. The same is true for the BCAP program. Forest Biomass for Energy allocates most of its funds to research single purpose. The PACE loans, for example, are suitable for all pellet sector, it can be concluded that in each of these provisions wood pellets are merely an inclusion, rather than a demand by providing subsidies for the end consumer. However, several remarks and considerations can be made. By providing funds for both the technical side as for the consumer side of the chain, the US government stimulates innovation in two ways. First, is fosters innovation directly by funding Research and Development and the manufacturing of pellets. Second, it stimulates demand by providing subsidies for the end-consumer. Although there seem to be quite some provisions that foster innovation in the wood pellet sector, it can be concluded that in each of these provisions wood pellets are merely an inclusion, rather than a single purpose. The PACE loans, for example, are suitable for all renewable energy appliances to be applied in a house and the Forest Biomass for Energy allocates most of its funds to research into biofuels. The same is true for the BCAP program. **6.3.2 Effect of policy on Carbon Cycle and the use of Wood Pellets** It is hard to tell what the exact influence of these policies is on the life cycle of pellets as a heating fuel. In figure 6, the different policies have been categorized and attached to the different parts of the life cycle. Two focuses become clear: the research and support of growing biomass. Farmers receive support in their efforts to grow and sell eligible biomass, whereas scientists get funds to find out more on sustainable harvesting and how forests can become more productive. These two

<table>
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<th></th>
<th>Provision of R&amp;D</th>
<th>Competence Building</th>
<th>Formation of new product markets</th>
<th>Articulation of quality requirements</th>
<th>Creating and changing organizations</th>
<th>Networking through markets</th>
<th>Creating and changing institutions</th>
<th>Incubating activities for innovation efforts</th>
<th>Financing of innovation processes</th>
<th>Provision of consultancy services</th>
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Table 14: Effect of government initiatives on innovation in the wood pellet sector

The table shows that the government stimulates Research and Development, but also the creation of new markets by subsidizing new consumers. Also, the government sets emission standards and creates legislation that allows consumers to participate in a beneficial loan program. Edquist does not elaborate on how these activities can be assessed on successfulness and it is beyond the scope of this research to do this. However, several remarks and considerations can be made. By providing funds for both the technical side as for the consumer side of the chain, the US government stimulates innovation in two ways. First, is fosters innovation directly by funding Research and Development and the manufacturing of pellets. Second, it stimulates demand by providing subsidies for the end-consumer. Although there seem to be quite some provisions that foster innovation in the wood pellet sector, it can be concluded that in each of these provisions wood pellets are merely an inclusion, rather than a single purpose. The PACE loans, for example, are suitable for all renewable energy appliances to be applied in a house and the Forest Biomass for Energy allocates most of its funds to research into biofuels. The same is true for the BCAP program.

![Figure 6: Policy in relation to pellet processing cycle](image)

![Figure 7: Total capacity of US and Canada pellet factories in 10^3 ton per year for 2003 through 2009, Source: Spelter & Toth (2009)](image)
matters are of vital importance to the carbon balance of pellet heat.

On the consumer side of the chain, two types of financial support can be observed. The tax credit is a Federal initiative and therefore available to every house owner. The PACE loans are available in various states and in some counties throughout the US. Also, an educational program is part of the inventory on the consumer side. Additionally, the emissions of biomass appliances have been regulated.

Three measures can be identified in order to assess the effects of these policies on the use of wood pellets as a heating fuel. First, there is the US Census Data, telling how many households use wood as their primary heating source. Second, figures are available on how the funds of the different programs are distributed across various purposes and lastly, the annual production of pellets can be examined as a means of surveying the impact of policy on the left side of the chain.

The US Census Data show that the percentage of households using wood as their primary source of heat is relatively low compared to all other sources of heat. In 2008 this percentage was 1.7% on average in the United States and has been steady since the year 2000. Although the Census does not give breakdowns by state after the year 2000, it is clear from historical data that this percentage tends to be higher than the national average in the New England States (around 3.5%). No data is available on what percentage of these wood users use pellets to fuel their installation. Another big concern about these figures is that it only gives the figures for households where wood is the primary source of heat. For example, households that heat only their living room with wood (pellets) are not included in this number. It is not unlikely that the number of people having a wood appliance installed in their home is a lot higher than the aforementioned number. Actual numbers, however, are not available.

According to Spelter & Toth (2009), the American wood pellet industry showed a steady rise in capacity over the last few years. As can be seen in figure 7, the capacity for pellet production, especially in the Southern US has grown substantially. This increase in pellet production has not necessarily led to an increase in pellet use by American households or power plants. The same paper shows that also the export of wood pellets has increased significantly. Figure 8 displays this growth.

7 Conclusion

Pellets as a heating fuel in domestic appliances can be considered as a low carbon fuel, relative to the alternative fossil fuels. The emissions of a pellet heating system can be as low as 6.04 g CO₂/MJ whereas its least polluting fossil counterpart emits 62.8 g CO₂/MJ. If the pellets are being transported overseas, the CO₂ emission would amount to 27.7 g CO₂/MJ. This is still less than half the figure for the lowest fossil heating fuel but the most optimal use of pellets is for application on a local scale.

The most influential parameters are the management of the forest the used wood is taken from and the transportation of the pellets. All the calculations are based on the premise that the harvested wood is regrown. As long as the wood is being harvested in a sustainable way, the low net CO₂ emission as determined in this paper can be achieved. It should be emphasized, however, that sustainable harvesting is absolutely necessary to maintain the delicate balance.

Another conclusion to be drawn from this study is that the transportation of sawdust pellets over long distances has considerable impacts. Nevertheless, even transatlantic transported pellets have a lower net CO₂ emission than heating with fossil fuels.

It is complex to assess what the exact role is over the government in this National System of Innovation. A few things, however, are observed: The government stimulates Research and Development through two different programs and two provisions exist that create or stimulate markets by reducing the costs for the end consumer. The common factor in all these programs is that wood pellets are only a part of the program and there are no programs catering exclusively to wood pellets. It is therefore hard to tell how big the influence is of this legislation on wood pellets and this would be an opportunity for further research. Neither is it clear what the influence of policy is on the use of wood pellets and on the carbon balance. It is evident that regulation of harvesting would be a great opportunity for the government to introduce legislation on, as this is the key to obtain a low carbon heating fuel.

8 Discussion

The first point to be discussed in with regards to the outcomes of this paper is that the source of the wood has not been taken into consideration. Although the source of the wood does not influence the carbon balance as a whole, its consequences are considerable for the timeline of the carbon neutrality. This problem can be addressed from two
angles: forest management and carbon neutrality definition.

In order to achieve the low emission as calculated in this paper, the combusted tree be regrown and the forest from which the wood has been taken should be managed in such a way that wood production can be sustainable. Currently, a huge debate is going on in the northeastern states as to what guidelines should be accepted for ‘sustainably harvested wood’. Not only should the productivity of the forest exceed the harvesting, but forest ecology, water quality and depletion of the soil should be guaranteed. Besides the definition of ‘sustainable’, another issue arises. Even if the harvest is considered sustainable, it may take years for a forest to grow back to its original volume. Therefore, one can ask on what time span you would consider this cycle still neutral. After all, even fossil fuels were once plants and have sequestered CO₂ before they were burned, but as recovery time involves millions of years, it is considered exhaustible.

Even though this debate about what is still in progress, this paper has attempted to come up with some figures on what amount of wood can be produced annually. Based on the assumptions made in this paper, one hectare could yield between 19.6 and 340 Mg wood/ha, depending on which the type of wood and the length of the harvesting cycle. These figures do not pretend to be accurate, but try to give the reader some insight in a figure for a typical production in the Eastern US. The sustainable productivity of forests throughout the US is a great opportunity for further research, and can be of great use in determining the potential of wood to replace fossil fuels.

The distances in the transportation cycle can also be a cause for discussion. In this paper, transportation from British Columbia, Canada is considered. However, big pellet manufacturers in Georgia, USA, transport also large amounts of pellets overseas, which is about half the distance. This shorter distance could lead to a considerable lowering of emissions during the transportation of the pellets.

Then, the emission data from combustion should be emphasized. The first thing to note is that the type of stove and burner used is not clear. The two pellet appliances are indicated in the paper by Kjallstad & Olsson (2004a) as Pellet Burner (20 kW) and Pellet Stove (7 kW), and besides the fact that both are top-fed, it is unclear which appliance is used. As the paper is written by Swedish authors, it is likely that a European appliance is used. An important argument to use this data regardless is that the authors consider their findings examples, rather than exact figures for specific devices. Therefore, these data can be used, as the cycle as described in this paper must be seen as an example of what a cycle as such may look like. The phenomena are similar for different species of trees and different types of pellet appliances, although differences in relative abundances of compounds in the emitted gases may appear.

Another point of concern is how to interpret the emission rates. These are given in mg/m³ and for the calculations in this paper, the assumption has been made that these rates are constant for the complete combustion of the pellets. Two arguments can be given to justify this assumption. The main point of using wood pellets rather than wood chips or logs is the homogenous composition and the low moisture content of pellets. Due to these features, the emission rates of pellet appliances are very continuous and therefore, the used data may be a good representation of the emissions of a pellet stove and pellet burner. Deviations in emitted fluxes only occur at the very beginning and end of combustion, but otherwise the emission rates are fairly constant.

The final point on the carbon side of this paper that needs attention is that, even though emissions on a macro scale are much lower than those from appliances fueled by fossil fuels, on a local scale the emissions are a lot higher. At the sites where the appliances are being used, higher concentrations of CO₂, CO, CH₄ and Benzene will be in the atmosphere than when fossil appliances are being used. This raises to arguments for not using wood heating in densely populated areas. Another sort of emission not discussed in this paper is that of particulate matter. Although this type of emission is relatively low compared to traditional fireplaces, it is still forthcoming and should therefore also be considered in further research.

It is hard to tell what the exact influence of policy is on the life cycle of pellets as a heating fuel. There seems to be a vast increase in the production and export of wood pellets over the last few years, but it is complex to assign a cause to this increase. It is tempting to relate the BCAP program to the increased production. Other reasons may concern the current economic crisis, uncertainty about oil supply and rising energy prices. Further research will have to decide what the exact reasons are. Further research will also have to examine the effects of the tax credit on the use of pellet appliances. Figures for 2009 and 2010 are lacking and as the tax credit has only been in force since fiscal year 2009, the exact effects are unknown.
## Appendix A: Retention Guidelines

<table>
<thead>
<tr>
<th>State</th>
<th>Forest Type</th>
<th>%Course Woody Debris</th>
<th># of Snags</th>
<th>Guideline development</th>
<th>Notes</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pennsylvania</td>
<td>Mostly evenaged, 90% hardwood species</td>
<td>Leave up to 15-30% of pre-harvest biomass (leave 1 out of every 3-6 harvested trees); 2-5 non-merchantable logs per acre</td>
<td>1-5 per acre; 5 trees with cavities</td>
<td>Literature review, professional/expert opinion of DNR staff and others</td>
<td>The forest floor, including roots, stumps and below-ground biomass is off limits; whole-tree harvesting limitations</td>
<td>PADCNR 2008</td>
</tr>
<tr>
<td>Missouri</td>
<td>Mostly hardwood species; pine occurs in the dryer Ozarks; 800-1200mm of precipitation a year, snow</td>
<td>Mechanized removal: Leave 1/3 tops and 1/3 small sized trees Chainsaw: leave 1/3 harvest residue (tops and branches) Leave as much FWD as possible</td>
<td>Retention of snags and den trees to leave per acre are based on habitat. Den trees: 3-25; snags: 3-12</td>
<td>Professional/expert opinion of MDC Forestry Division staff and stakeholders</td>
<td>Green tree retention: Leave some mast trees; 5inches DBH or less- leave 200 trees 5-10inches DBH- leave 150 trees 11inches DBH or greater- leave 80-100 trees</td>
<td>Enyart 2008</td>
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<tr>
<td>Wisconsin</td>
<td>Mixed hardwoods; red, white, jack pine; fir-spruce pine; white cedar. Cold, snowy winters and warm summers; 2/3 of annual precipitation falls during the growing season</td>
<td>Retain FWD and CWD already present; retain tops and limbs from 10% of trees 4inches DBH or smaller; leave at least 2-5 bark-on downed logs (12inches DBH or greater) per acre</td>
<td>Leave as many snags as possible</td>
<td>Literature review, professional/expert opinion</td>
<td>General and site (soil) specific guidelines presented. Do not remove litter layer, stumps or roots. Green tree retention: 6-12 trees on clearcut sites, 6 cavity trees on non-clearcut sites</td>
<td>Herrick et.al. 2008</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>Uneven aged management dominates; Mixed Oak, White Pine, Northern Hardwood, Hemlock, Mixed Hardwood</td>
<td>Leave CWD on ground</td>
<td></td>
<td>Literature review; professional/expert opinion</td>
<td>Avoid whole-tree clearcut harvest, where all woody biomass is removed; retain 10-20% of the stand in intact forest</td>
<td>Kelty et. al. 2008</td>
</tr>
<tr>
<td>State</td>
<td>Management Details</td>
<td>Leave CWD on Ground</td>
<td>Literature</td>
<td>Avoid whole-tree clearcut harvest, where all woody biomass is removed; retain 10-20% of the stand in intact forest patches</td>
<td>Reference</td>
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<tr>
<td>Massachusetts</td>
<td>Uneven aged management dominates; Mixed Oak, White Pine, Northern Hardwood, Hemlock, Mixed Hardwood</td>
<td>Leave CWD on ground</td>
<td>Literature review; professional/expert opinion</td>
<td>Do not move forest floor, litter layer, stumps or root systems. Retain slash piles that show use by wildlife. Retain 20% understory vegetation in reserve patches</td>
<td>Kelty et. al. 2008</td>
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<tr>
<td>Minnesota</td>
<td>Hardwoods; conifers; mixed stands; wet and dry sites; cooler average temperatures</td>
<td>Leave all pre-existing CWD possible; 1/3 FWD retained on site-retain and scatter tops and limbs from 20% of the trees harvested and the rest will come from incidental breakage; leave 20% of brush and small trees if biomass removal is associated with timber harvest.</td>
<td>Literature review; professional/expert opinion</td>
<td>Literature review; professional/expert opinion; empirical data collected from harvest case studies</td>
<td>MFRC 2007</td>
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<tr>
<td>Maine (Draft)</td>
<td>Spruce and Fir forest; Northern Mixed Hardwood; White pine forest</td>
<td>Retain as many down logs as possible; retain as much FWD as possible- scatter tops and branches across the harvest area.</td>
<td>Literature review; professional/expert opinion</td>
<td>Retain live cavity trees, trees with rot, mast trees; retain trees, snags and down logs in patches across the landscape</td>
<td>Benjamin 2009</td>
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<tr>
<td>Oregon</td>
<td>Douglas-fir; mixed conifer/deciduous; pine; true fir, hemlock and Sitka spruce. Mostly wet, but some dry eastern sites.</td>
<td>Two downed pieces of wood per acre</td>
<td>Literature review; professional/expert opinion</td>
<td>Covered in the Oregon Forest Practices Act-regulations are triggered when harvests are of a certain size (&gt;25 acres) and stocking density is reduced below a certain amount.</td>
<td>Behan and Misek 2008</td>
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